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LOW-ANGLE NORMAL FAULTING AND ISOSTATIC RESPONSE IN THE GULF OF SUEZ: EVIDENCE FROM SEISMIC INTERPRETATION AND GEOMETRIC RECONSTRUCTION: S. K. Perry and S. Schamel, Earth Sciences and Resources Institute, University of South Carolina, Columbia, SC 29208

Tectonic extension within continental crust creates a variety of major features best classed as extensional orogens. These features have come under increasing attention in recent years, with the welding of field observation and theoretical concepts providing new insights. Most recent advances have come from the Basin and Range Province of the southwestern United States and from the North Sea (1, 2). Application of these geometric and isostatic concepts, in combination with seismic interpretation, to the southern Gulf of Suez, an active extensional orogen, allows generation of detailed structural maps and geometrically balanced sections which suggest a regional structural model. This paper concentrates on geometric models which should prove to be a valuable adjunct to numerical and thermal models for the rifting process.

Regional Geology

The Gulf of Suez, Red Sea and Gulf of Aqaba rifts form the northernmost extensions of the East African rift system (Fig. 1). The African and Arabian plates are moving apart, creating new oceanic crust in the southern Red Sea and the Gulf of Aden. The Suez rift is separated from the Red Sea by the Gulf of Aqaba transtensional system. The Suez rift itself lies between the African continent and the Sinai Peninsula. Elevated and eroded rift shoulders form extensive crystalline basement outcrops and bound a deep trough floored by a complex tilt-block mosaic and filled with synrift sediments. Total estimates of extension usually range around 25% (3).

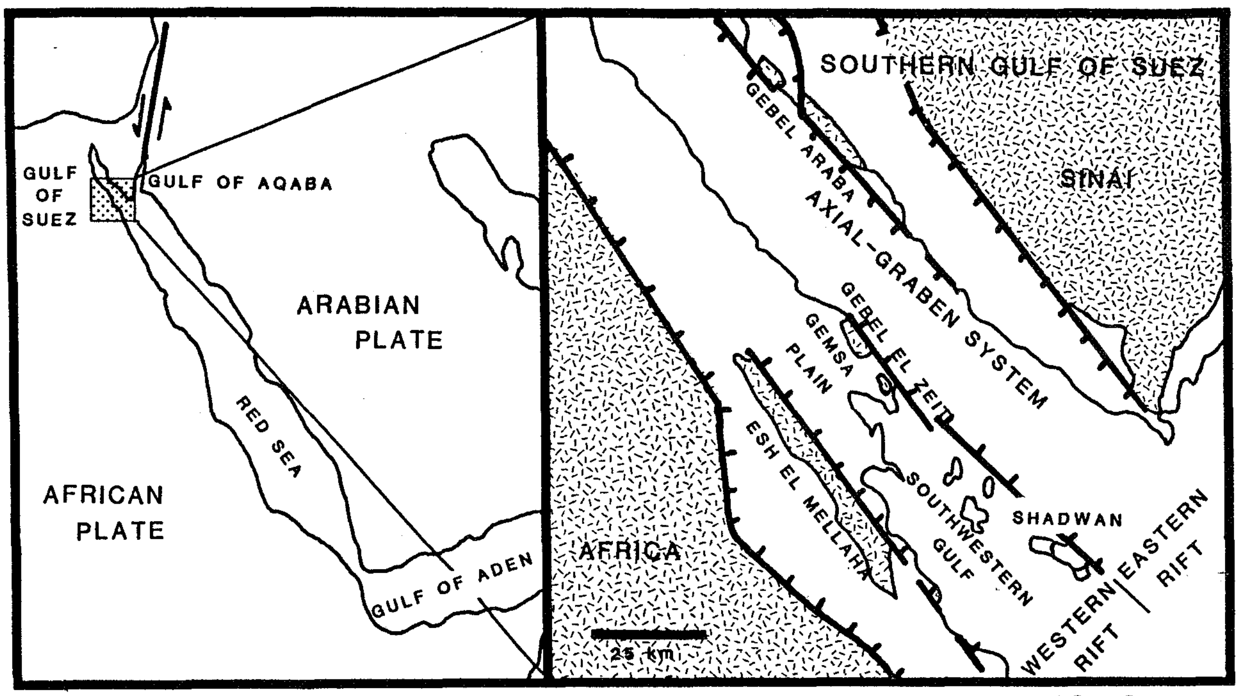


Figure 1: Regional geography of NE Africa and the southern Gulf of Suez.

Three rock groups are present: (1) an extremely complex Precambrian basement terrane; (2) widespread, relatively continuous prerift, Cambrian-Eocene platform sedimentary rocks; and (3) widely varying synrift fill of predominantly Neogene age. The basement and overlying platform succession were broken into numerous rift-parallel tilted fault blocks beginning in the Oligocene. Erosion stripped the top of the highest blocks and the rift shoulders, shedding clastics around the tilt block perimeters. Flooding of the rift in the early Miocene led to mixed carbonate and clastic deposition. During the middle Miocene, restricted conditions led to a build up of thick cyclic evaporites. Terrestrial and shallow marine depositional environments still dominate the gulf. Structural movements have continued through the present, with fresh fault scarps clearly visible and occasional earthquakes occurring.

## Structural Geometries and Timing

Cross-strike variations in structural geometries and fault timing divide the southern Gulf of Suez into two major structural domains. The western portion of the rift preserves an early tilt-block mosaic, while the eastern half of the rift shows the superimposed development of a axial system of grabens probably bordered by relatively young steep faults.

Western rift. The western portion of the southern Gulf of Suez contains three discrete structural domains, each comprising a broad SW-dipping half-graben sub-basin floored by smaller tilt blocks having similar orientations (Fig. 1). The westernmost half-graben lies between the western border fault of the rift and the major bordering fault defining the eastern edge of the Esh el Mellaha tilt block. The other two half-grabens are along strike from one another immediately to the east and are delineated by the Esh el Mellaha border fault and the Gebel el Zeit-Shadwan Island structural high. These are the Gemsa Plain half-graben in the northwest and the southwestern Gulf of Suez immediately to the southeast. The two regions are separated by a zone of anomalous structures around Ras el Bahar.

Both the Gemsa Plain and southwestern Gulf of Suez half-grabens were analyzed in detail. Surface studies in the Gebel el Zeit and Esh el Mellaha ranges in combination with interpretation of seismic reflection data and well logs provided constraints for the construction of serialized, geometrically restorable cross sections. Subsurface information for the structurally simple Esh el Mellaha domain is not available. These sections, in combination with seismic structure maps, allowed construction of internally consistent, geometrically constrained structural maps. This has not previously been feasible in the Gulf of Suez because of ambiguities inherent in the seismic reflection data.

Differences in structural style and extensional quantity show that extension within the the rift is partitioned into discrete units on several scales. On the largest scale, the major structural domains are bounded by master listric faults and exhibit roughly uniform internal extension. In contrast, the amount of internal extension may differ substantially between these domains. It can be assumed that the total extension across the rift is equal, or decreasing gradually to the north. Similarly, the large tilt domains may be broken into suites of *en echelon* blocks along both listric and planar faults, themselves representing smaller scale partitioning of the extension within the domain.

Within this context, the southwestern Gulf of Suez half graben forms a discrete structural domain with roughly 15% internal extension. This is partitioned into numerous smaller, fault-bounded structural highs that rise and fall along strike, always maintaining approximately the same extension across the domain. In contrast, the Gemsa Plain was initially narrower than the southwestern Gulf and appears to represent roughly 50% extension. In this case, the domain is dominated by a single major tilt block, the Zeit block (Fig. 1). The western edge of this block lies deeply buried under the Gemsa Plain, abutting the Esh el Mellaha's eastern border fault, and the eastern, or leading, edge forms the complexly deformed Gebel el Zeit ranges. Between the two domains lies a transitional region of confused geology and limited data. Geometrically balanced sections show that both half grabens result from movement over an initially east-dipping and now subhorizontal detachment lying at roughly 30,000 feet. Furthermore, both domains are bordered on the east by through-going high-angle faults which break the original detachment. Some other portions of the region are also broken by these faults. These faults clearly post-date major tilt-block movement over the detachment.

The sedimentary fill of the sub-basins within the two half grabens shows the structural timing within the western gulf. Initial movements on the primary listric border faults of the half grabens occurred prior to the deposition of basal redbeds during the uppermost Oligocene. Very gentle tilting continued through the deposition of marine clastics, carbonates and evaporites of the Nukhul Formation which is probably of Aquitanian age. Rapid environmental differentiation and strongly tilted strata show that the half grabens developed rapidly during the early Burdigalian, with the southwestern Gulf half graben fragmenting into a suite of smaller tilt blocks. Erosion cut into the tilt-block crests and both capping and fringing reefs formed. These are preserved *in situ* along the Esh el Mellaha range and show no structural tilting, indicating that the Esh el Mellaha half graben stopped developing during the Burdigalian, when a major pause in structural activity is reported. The remainder of the western rift continued to develop rapidly with block tilts increasing steadily. Major tilting in the southwestern Gulf slowly decreased during deposition of middle and upper Miocene evaporites, with uniform gradual subsidence continuing. The Gemsa Plain sub-basin shows greater subsidence and tilting with less environmental differentiation. A major angular unconformity and both Pliocene and Pleistocene raised and tilted carbonates and beach terraces show continuing block tilting, while relatively thick Plio-Pleistocene clastics conformably overlie Miocene evaporites in the deeper portions of the sub-basin. Through-going faults greatly deform the Miocene section along the eastern margins of both half grabens indicating predominantly Pliocene and later movements.

*Eastern Rift*. Published descriptions and new studies of oil fields and surface outcrops in the eastern rift show that it differs from the western rift in both structural style and timing, with much more pronounced late development. During the Aquitanian and lower Burdigalian the eastern rift shows a structural development similar to that in the west, but with less well-defined half grabens, less throw on faults and thinner synrift deposits than in the west. During the upper Burdigalian and continuing into the middle Miocene the Sinai rift shoulder became eleveated, a broad tilt-block bench remained near sea level around Gebel Araba, and an *en echelon* series of grabens broke the region between the Sinai rift shoulder and the Gebel el

Zeit-Shadwan Island high, forming an axial-graben system. This movement waned during the upper Miocene, as do most structural movements in the Gulf, but accelerated rapidly during the Plio-Pleistocene. Subsidence in the axial-graben system during this time allowed local deposition of greater thicknesses of clastics and carbonates in the last 5 my than had been deposited in the Miocene. The formation of the axial-graben system also marks a great change in structural style, with subsidence between relatively steeply dipping and oppositely facing normal faults substituting for earlier rapid tilting.

Tectonic Model for the Southern Suez Rift

The three aspects of the Suez rift described above bear directly on its structural evolution: (1) the early Miocene development of a tilt-block mosaic forming and array of broad half grabens and focused in the west; (2) eastward propogation of deformation to the eastern rift during the early Miocene; and (3) the predominantly middle Miocene-through-Recent formation and growth of a depressed axial-graben system bordered by relatively high-angle faults.

We suggest that this pattern is a result of tilt-block movement over a low-angle detachment whose subsequent isostatic upwarping localized deep-seated deformation and forming the axial-graben system (4). Initial NNE-SSW extension during the Oligocene and earliest Miocene was accompanied by minor rotation on wide listric tilt blocks over a regional east-dipping low-angle detachment which formed half-graben sub-basins filled with thin redbed and Nukhul Formation sediments (Fig. 2-A). With increasing extension during the Burdigalian tilt-block rotation continued, extensionally thinning the upper crust over a passive lower crust. In response, isostatic uplift of the passive lower crust warped the detachment and overlying terrane into a broad arch, limiting gravity-driven tilt-block movement in the west (5) and creating a rift-parallel high in the Moho. This uplift stalled movement on the Esh el Mellaha

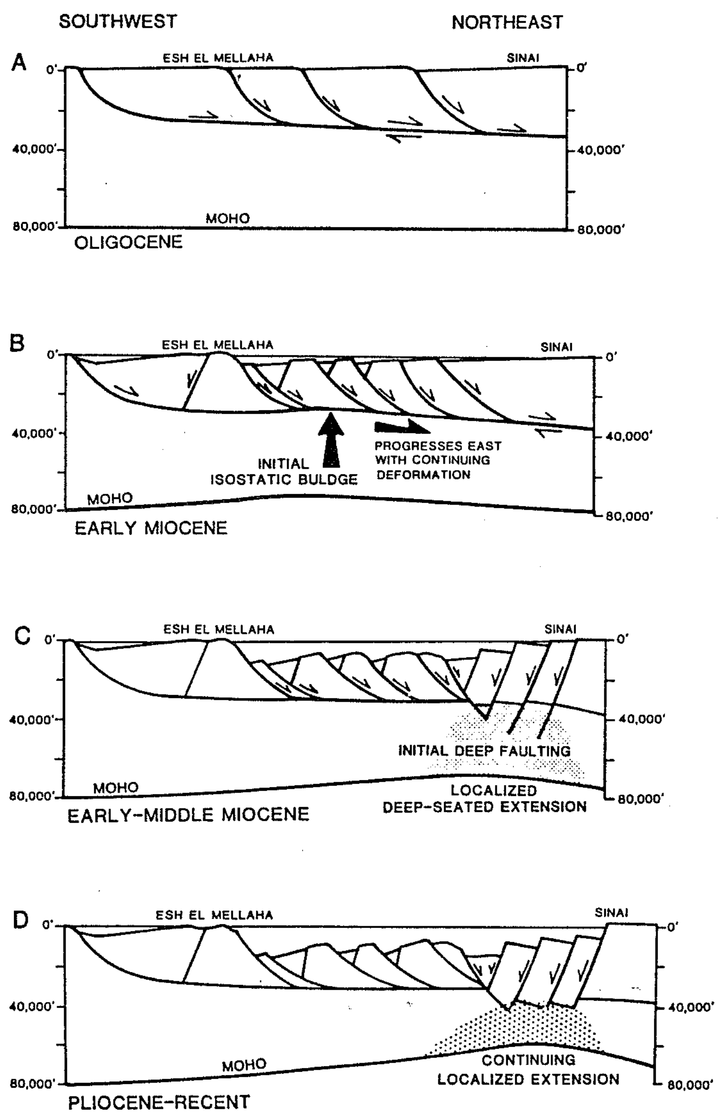


Figure 2: Evolutionary model.

tilt block by decreasing the dip of the detachment but allowed extension to concentrate within the southwestern Gulf by increasing detachment dip (Fig. 2-B). Deposition of the thick lower Miocene shales and marls resulted. With further extension during the upper Burdigalian, continuing isostatic uplift progressively uplifted and flattened the detachment beneath the southwestern Gulf and shifted the axis of the isostatic arch to the eastern rift (Fig. 2-C). At this point the majority of tectonic development in the west was complete. In conjunction with the uplift of the Sinai rift shoulder, probably a thermal response, a new set of relatively high-angle normal faults cut through the old detachment forming the axial-graben system. This faulting was greatly reactivated during the Plio-Pleistocene, a time of increased spreading in the Red Sea (6). These younger faults may root into a deeper detachment within more thermally mature crust, may merge directly into a zone of ductile flow under the rift, or may splay up from a zone of active intrusion within the lower crust. We favor this last possibility since mantle-derived oceanic crust must eventually form with continuing extension, as is shown in the southern Red Sea. This model is consistent with the observed early breakup of the rift into a series of broad half grabens and explains the eastward shift of deformation through time, the early cessation of rapid tilt-block movement in the west, and the late formation of a a depressed axial-graben system in the east.

This research suggests that early movement over low-angle detachments plays an important role in localizing deformation within rifts, and is undoubtedly a critical element in the formation of passive margins.

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